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Institute of Mathematical Sciences
Division of Electromagnetic Research

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A Note on the Local Structure of Shot Noise

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A NOTE ON THE LOCAL STRUCTURE OF SHOT NOISE

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It is well known that the random velocity field produced by wind tunnel turbulence at high Reynolds numbers has the following statistical structure: Let the x axis be directed downstream beyond the grid generating the turbulence and let $u_1(x,y,z)$ be the downstream component of the random velocity field, measured at any point of the flow. Then, to a good approximation, $u_1(x,y,z)$ is a normal random variable, i.e., the velocity field is quite accurately univariate normal. If the field were bivariate normal as well, then writing $\delta u(r) = u_1(x+r,y,z) - u_1(x,y,z)$, where again (x,y,z) is any point of the flow, we would expect the random variable $\delta u(r)$ to be normal, in particular to have a skewness $\gamma(r) = E[\delta u(r)]^3 / \{E[\delta u(r)]^2\}^{3/2}$ equal to zero and a flatness $\phi(r) = E[\delta u(r)]^4 / \{E[\delta u(r)]^2\}^2$ equal to three, the appropriate values for a normal random variable.*

What is actually found to be the case instead is that $\gamma(r)$ and $\phi(r)$ are appreciably different from zero and three, respectively, for values of r such that the correlation function $f(r) = E[u_1(x+r,y,z) \cdot u_1(x,y,z)] / E[u_1(x,y,z)]^2$ is appreciably different from zero. For experimental values of $\gamma(r)$ and $\phi(r)$ and a detailed discussion of the statistical structure of turbulence, we refer to the last chapter of Batchelor's monograph. [1]

The state of affairs just described raises the following

*The symbol E denotes the expectation value or ensemble average.

question: Is it possible by suitably choosing the shot rate and the pulse shape to construct shot noise which mimics the statistical structure of turbulence, i.e., which is quite accurately univariate normal but exhibits marked departures from bivariate normality at close ranges? The answer is in the affirmative, as we shall now show. For simplicity, we consider first the case of a one-dimensional random process

$$(1) \quad u(t) = \sqrt{\frac{2}{\rho}} \sum_{i=-\infty}^{\infty} \beta_i s(t-t_i) - c \sqrt{\rho}$$

where the t_i are the random occurrence times of the events in a stationary Poisson process with an average rate of ρ events per second. The β_i are a family of independent random variables, all uniformly distributed over the unit interval $(0,1)$. The centering

constant c is chosen to be $\sqrt{\frac{2}{\rho}} \int_{-\infty}^{\infty} s(t) dt$, which assures that $Eu(t) = 0$,

and the normalization is such that $Eu^2(t)$ is independent of ρ and is

in fact equal to $\int_{-\infty}^{\infty} s^2(t) dt$. (The author has given a similar construction elsewhere.)^[2]

We must now suitably choose the pulse shape $s(t)$ and the rate ρ so that the random variable $u(t)$ is quite accurately normal, while for small τ the difference random variable $u(t+\tau) - u(t)$, in particular $u'(t) \equiv du(t)/dt$ corresponding to the limit $\tau \rightarrow 0$, is quite markedly non-normal.* To achieve this, we choose $s(t)$ to be the function

*The parameter t is fixed but arbitrary.

$$(2) \quad s(t) = \begin{cases} t/2\epsilon & , \quad 0 \leq t < 2\epsilon & , \\ 1 & , \quad 2\epsilon \leq t < \alpha - \epsilon & , \\ (\alpha - t)/\epsilon & , \quad \alpha - \epsilon \leq t < \alpha & , \\ 0 & , \quad \alpha \leq t & , \end{cases}$$

with derivative

$$s'(t) = \begin{cases} 1/2\epsilon & , \quad 0 \leq t < 2\epsilon & , \\ 0 & , \quad 2\epsilon \leq t < \alpha - \epsilon & , \\ -1/\epsilon & , \quad \alpha - \epsilon \leq t < \alpha & , \\ 0 & , \quad \alpha \leq t & , \end{cases}$$

where $\epsilon \ll \alpha$ is a small parameter to be adjusted later. Our choice of $s(t)$ is motivated by the fact that its support (α) is much larger than the support (3ϵ) of its derivative; the significance of this will emerge presently. We have also arranged to give $u'(t)$ a negative skewness, in order to resemble the turbulent velocity field.

We now use the fact that the semi-invariants μ_n of $u(t)$ are given by the formula

$$\mu_n = \rho \left(\frac{\beta}{\rho} \right)^{\frac{n}{2}} E \beta^n \int_{-\infty}^{\infty} s^n(t) dt \quad ,$$

where β is any of the β_i . [3] In our case $E \beta^n = \frac{1}{n+1}$, since β is uniformly distributed over the interval $(0,1)$; the inclusion of the random variables β_i in the expression (1) is to assure that the distributions of $u(t)$ and $u'(t)$ contain no delta function terms. In view of the relations $\mu_2 = m_2$, $\mu_3 = m_3$ and $\mu_4 = m_4 - 3m_2^2$ between the

semi-invariants μ_2 , μ_3 and μ_4 and the central moments m_2 , m_3 and m_4 , we find that the skewness of $u(t)$ is given by

$$\gamma = \frac{\mu_3}{\mu_2^{3/2}}$$

and its flatness by

$$\phi = 3 + \frac{\mu_4}{\mu_2^2}$$

For the case of the pulse shape (2), we find that

$$\gamma = \frac{3}{4} \sqrt{\frac{2}{\rho}} \frac{\alpha - \frac{9}{4} \epsilon}{(\alpha - 2\epsilon)^{3/2}} \sim \frac{1.3}{\sqrt{\rho\alpha}}, \text{ if } \epsilon \ll \alpha,$$

and

$$\phi = 3 + \frac{9}{5\rho} \frac{\alpha - \frac{12}{5} \epsilon}{(\alpha - 2\epsilon)^2} \sim 3 + \frac{1.8}{\rho\alpha}, \text{ if } \epsilon \ll \alpha,$$

so that for small ϵ/α , the condition $\sqrt{\rho\alpha} \gg 1$ assures that $u(t)$ is quite accurately normal. [4] On the other hand, differentiating (1), we see that the univariate distribution of the process $u'(t)$ is governed by the semi-invariants

$$\mu_n' = \rho \left(\frac{3}{\rho}\right)^{\frac{n}{2}} \mathbb{E} \beta^n \int_{-\infty}^{\infty} [s'(t)]^n dt,$$

with corresponding skewness

$$\gamma' = -\frac{3}{4} \frac{1}{\sqrt{2\rho\epsilon}} \sim -0.5 \frac{1}{\sqrt{\rho\epsilon}},$$

and flatness

$$\phi' = 3 + \frac{0.9}{\rho\epsilon}.$$

Examining the expressions for γ , ϕ , γ' and ϕ' , we see that by satisfying the conditions $\sqrt{\rho\alpha} \gg 1$ and $\sqrt{\rho\epsilon} \sim 1$, we can arrange to have simultaneously a quite accurately normal distribution of $u(t)$ and a markedly non-normal distribution of $u'(t)$. Moreover, the two conditions $\sqrt{\rho\alpha} \gg 1$ and $\sqrt{\rho\epsilon} \sim 1$ are compatible, provided only that $\sqrt{\alpha/\epsilon} \gg 1$. For example, if $\alpha = 1$, $\epsilon = 10^{-4}$ and $\rho = 10^4$, we have $\gamma \sim 0$, $\phi \sim 3$, $\gamma' \sim -0.5$ and $\phi' \sim 3.9$.

The skewness $\gamma(\tau)$ and the flatness $\phi(\tau)$ of the difference $u(t+\tau) - u(t)$ can be calculated in just the same way by observing (following a suggestion of E. N. Gilbert) that the process $u(t+\tau) - u(t)$ is given by (1) if we replace $s(t)$ by $s(t+\tau) - s(t)$. It is found that as $\tau \rightarrow 0$, $\gamma(\tau)$ and $\phi(\tau)$ reduce continuously to the limiting values γ' and ϕ' , and that as τ approaches the correlation distance α of the process $u(t)$, $\gamma(\tau)$ and $\phi(\tau)$ approach the normal values of zero and three.* Thus $u(t)$ resembles the turbulent velocity field by

*The correlation function of $u(t)$ is

$$\frac{\int_{-\infty}^{\infty} s(t+\tau)s(t)dt}{\int_{-\infty}^{\infty} s^2(t)dt},$$

which vanishes for $\tau \geq \alpha$. The function $\gamma(\tau)$ undergoes a sign change in the interval $(0, \alpha)$.

having a markedly non-normal bivariate distribution at close ranges.

Precisely the same kind of construction can be carried out in three dimensions by replacing the random times t_i by a spatial Poisson distribution and replacing the pulses $s(t)$ by three-dimensional "blobs". For example, suppose that

$$u(x,y,z) = \sqrt{\frac{2}{\rho_V}} \sum_i \beta_i s(x-x_i) s(y-y_i) s(z-z_i) - c \sqrt{\rho_V} ,$$

where the function s is the same as in (2), while this time ρ_V is the volume density of the points (x_i, y_i, z_i) of a homogeneous spatial Poisson process and the summation is over all the "centers" (x_i, y_i, z_i) . For each point (x_i, y_i, z_i) , β_i is an independent random variable, uniformly distributed over the interval $(0,1)$. The centering constant

$$c \text{ is now } \frac{\sqrt{3}}{2} \left\{ \int_{-\infty}^{\infty} s(x) dx \right\}^3, \text{ and } Eu(x,y,z) = 0, Eu^2(x,y,z) = \left\{ \int_{-\infty}^{\infty} s^2(x) dx \right\}^3 .$$

For the skewness γ and the flatness ϕ of the

random variable $u(x,y,z)$, we now have

$$\gamma \sim \frac{1.3}{\sqrt{\rho_V \alpha^3}} , \quad \phi \sim 3 + \frac{1.8}{\rho_V \alpha^3} ,$$

while for the skewness γ' and flatness ϕ' of the random variable

$\frac{\partial}{\partial x} u(x,y,z)$, we find*

$$\gamma' \sim -\frac{3}{4} \frac{1}{\sqrt{2\rho_V \alpha^2 \epsilon}} \sim -0.5 \frac{1}{\sqrt{\rho_V \alpha^2 \epsilon}},$$

$$\phi' \sim 3 + \frac{0.9}{\rho_V \alpha^2 \epsilon}.$$

If $\sqrt{\rho_V \alpha^3} \gg 1$ and $\sqrt{\rho_V \alpha^2 \epsilon} \sim 1$, the random field $u(x,y,z)$ is quite accurately univariate normal but exhibits marked departures from bivariate normality at close ranges. These two conditions are compatible, provided that $\sqrt{\alpha/\epsilon} \gg 1$, as before. For example, if $\alpha = 1$, $\epsilon = 10^{-4}$ and $\rho_V = 10^4$, we have $\gamma \sim 0$, $\phi \sim 3$, $\gamma' \sim -0.5$ and $\phi' \sim 3.9$.

In conclusion, we see that when a large number of elementary waveforms are superimposed, even with high density and considerable overlap, there is no reason to expect a priori, in the absence of detailed information about the shape of the waveforms, that the resulting process is accurately normal.

*We use the obvious modifications of the formulas for the semi-invariants μ_n and μ'_n .

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